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Data Science in Support of Radiation Detection for Border Monitoring: An Exploratory Study

Abstract

Radiation detection technology is widely deployed in support of bordering monitoring, with the goal of identifying undeclared nuclear or radiological materials whilst in transit. However, the effective use of such systems is complicated in certain environments by the presence of significant quantities of naturally occurring radioactive materials. These trigger nuisance alarms, which can serve to divert attention from other investigations and result in the raising of alarming thresholds. This article explores how data science tools could support alarm assessment efforts. Drawing on a small real-life dataset of naturally occurring radioactive materials occupancies, dynamic time warping and agglomerative hierarchical clustering are used to preferentially group similar commodities based on their alarming spatial gamma profile, as they pass through a radiation portal monitor. Following further testing and development, this approach could provide new insights into alarming cargo, helping to significantly reduce time spent resolving nuisance alarms by characterising NORM at the primary scanning stage.

Key Words: Nuclear Security; Radiation Portal Monitors; Border Monitoring; Nuisance Alarms; Naturally Occurring Radioactive Materials; Alarm Assessment; Data Science; dynamic time warping; clustering.

Introduction

International concerns over the clandestine movement of sensitive nuclear and radiological materials across borders have been present for more than seventy years.¹ These have served to drive the development and deployment of systems targeted at identifying and intercepting radioactive materials as they are trafficked. Post-9/11, there has been a dramatic increase and internationalisation of these efforts, precipitated by a perceived upsurge in the capability and interest of non-state actors to acquire and use such materials in an act of nuclear terrorism.² Over the past two decades billions of dollars have been spent on the installation of radiation detectors for this purpose.³ Here US-led programmes alone, such as the Container Security Initiative (CSI) and the Megaports Initiative, have supported the installation and operation of systems at seaports, airports, road and rail border crossing points in more than 50 countries.⁴

However, despite significant investment in this area, there exists long-standing challenges to the sensing and characterisation of key threat materials, such as trafficked highly enriched uranium (HEU) and plutonium.⁵ As it is believed that these will most likely be shipped in small quantities and intentionally shielded by adversaries, reducing their radioactive emissions.⁶ Detection challenges are arguably most acute within the maritime supply chain, as in this environment large scale shipments of NORM and commercial radioactive goods, regularly trigger detection systems causing nuisance alarms.⁷ Examples include ceramics, fertilizers, granite, radiopharmaceuticals and industrial sources.⁸ The resolution of these alarms diverts the time and attention of officials from other investigations and reduce the speed of trade flows. High-levels of nuisance alarms can also lead to the raising of alarming thresholds, reducing the ability of systems to detect low radiative materials such as shielded HEU.⁹

A 2019 study estimated that at seaports NORM shipments are responsible, on average, for triggering an alarm for every 1.66% of total containers scanned.¹⁰ This is a small but nevertheless potentially significant percentage given high global seaborne trade volumes and a long-standing drive by the United States towards 100% scanning of imported containers.¹¹ For example, the throughput of world's busiest port Shanghai International in China, surpassed 40 million twenty-foot equivalents units (TEU) in 2017, equivalent to the daily processing of more than 100,000 containers.¹² Consequently at a large maritime facilities hundreds of nuisance alarms may be triggered by NORM in a single day.

This paper explores the potential utility of data science techniques in combating the challenge posed by nuisance alarms in the maritime environment, focusing on their resolution at the initial scanning stage. To this end Dynamic Time Warping (DTW) is performed on spatial radiation profiles generated by alarming containers as they are passed through Radiation Portal Monitors (RPMs). Applied in this context DTW seeks to account for variations in speed so that alarming containers can be meaningfully compared, and their degree of similarity calculated. Agglomerative hierarchical clustering is then employed to group similar warped RPM spatial radiation profiles in an effort to identify common NORM commodity types. Tens of millions of RPM occupancies are created and recorded every year, including hundreds of thousands of alarming records.¹³ However, systematic analysis of this data has so far been limited to the drawing of 'inferences about the stream of commerce and the pace of operations at sites'.¹⁴ Studies to date have not explored how this information might be harnessed using data science tools in support of the real-time assessment of alarms.

To help situate this research, the paper continues by summarising radiation detection processes, challenges and practice at maritime facilities. It discusses both existing and proposed systems, with a focus on the scanning of shipping containers, which comprise this

study's dataset. An introduction to DTW and its utility in analysing time-series data is then provided, before being applied to a real-life dataset of RPM spatial radiation profiles for alarming occupancies triggered by NORM.¹⁵ The relative dissimilarity of these warped profiles is then compared using agglomerative hierarchical clustering, creating groups of similar objects. These are illustrated as dendrograms and show a preferential clustering of common NORM commodities. The key results of this study are then summarised, with suggestions for future work.

Radiation Detection at Maritime Facilities – Current and Proposed Systems

At maritime facilities containerised cargo may be inspected for the presence of nuclear and radiological materials during import or export – when passing through a Point of Entry or Exit; or for transshipments during the process of loading and unloading.¹⁶ Typically, multi-stage detection protocols are employed, with alarming containers undergoing a series of evermore intrusive inspections until the cause is satisfactorily determined. A key component of radiation detection systems are RPMs. These are passive, non-intrusive detectors which are widely employed in the large-scale primary scanning of cargo at maritime (and other) facilities. In a primary inspection a container is slowly passed through an RPM, which detects any emitted gamma and neutron radiation over the course of its occupancy.

The presence of neutrons is relatively rare in most environments and so would automatically trigger an RPM alarm and follow-up investigation. In contrast there are many potential sources of gamma radiation, which necessitates the setting of a gamma count threshold.¹⁷ If the total gamma radiation received is above this threshold an alarm is triggered. The spatial gamma profile of a container as it transits the RPM is also captured and visually examined by officials for anomalies. For example, the presence of a sharp spike that might indicate a strong radioactive point source.¹⁸ RPM gamma and neutron information is assessed in conjunction with the shipment manifest, which contains information on the declared content of the container.

The spectral resolution of RPMs currently deployed are limited and so following an alarm a secondary inspection may be performed in an effort to characterise the radiation source. In a secondary inspection a container is typically moved to a secure area before a manual external inspection is conducted with passive handheld radioisotope identification devices (RIIDs).¹⁹ Gamma and X-ray images of the container may also be taken during a secondary inspection in order to identify any dense materials that might be shielding radioactive emissions. If a secondary inspection is also inconclusive then a further tertiary inspection may be launched, whereby the container is opened, and its contents unpacked. The level of

disruption to cargo flows will increase significantly if secondary and tertiary inspections are triggered. As while a primary inspection can be conducted in less than a minute, a secondary inspection might take tens of minutes and a tertiary inspection could take several hours.²⁰

Challenges in Assessing Alarms and Variations in Practice

It is an intrinsically difficult task to identify and characterise low radioactive threat materials in an environment where significant quantities of NORM and commercial radioactive goods are rapidly shipped. Although the presence of radiation can be detected during the short time it takes for container to transit an RPM, radioisotope identification – an important step in resolving nuisance and other alarms – currently requires at least a secondary inspection, which takes substantially longer. Secondary inspections can also be inconclusive as RIIDs may struggle to detect the relatively low activity of NORM containing commodities.²¹ These challenges are compounded by fluctuating local factors relating to the ambient environmental conditions and the detector setup, which can affect the radiation received, further complicating alarm assessment. These include the weather, the separation of the RPM detectors, their volume and ‘cross-talk’ from other containers in the nearby vicinity.²²

How detection systems are practically deployed is shaped by the priorities of different national detection programmes, the environment, available resources and commercial considerations. These influencing factors are frequently in tension and a difficult compromise between them will often have to be reached. For example, the determination of RPM alarming thresholds and when to trigger secondary and tertiary inspections, will be dictated by a combination of both the radiative properties of key threat materials and the need to maintain “flow efficiency” as a precursor for attracting business.²³ At some facilities security considerations dominate, while at others the management of nuisance alarms largely dictate how detection systems are set-up and operated.²⁴ This can result in considerable variation in approach from facility to facility. For example, a recent study by one of the authors, revealed that RPM nuisance alarm rates ranged from more than ten percent to less than one percent across facilities.²⁵ Even greater divergence was seen in the use of secondary inspections, following an initial RPM alarm, which were triggered at some facilities in over ninety percent of cases and at others in less than one percent of cases.²⁶

Efforts to Improve the Operation of Detection Systems for Border Monitoring

There has been considerable research and development work aimed at enhancing the ability of systems at maritime (and other) facilities to detect and swiftly characterise radioactive materials. A significant proportion of this work has been focused on the initial scanning of

cargo, as the ability to accurately identify the cause of alarms at this stage would alleviate the need for time intensive secondary and tertiary inspections. For example, tens of millions of dollars have been invested on Spectroscopic Portal Monitors (SPMs), which offer the promise of both high-sensitivity and spectral resolution.²⁷ In theory SPMs could be able to provide both simultaneous radiation detection and nuclide identification during initial primary scanning.²⁸ However, SPMs have so far struggled to meet operational requirements in certain environments, in particular at maritime facilities, and their deployment to date has been limited.²⁹

Other efforts have sought to improve the ability of existing systems. For example, the International Atomic Energy Agency's (IAEA) mobile application Tool for Radiation Alarm and Commodity Evaluation (TRACE), which provides a readily accessible database of NORM with information on the specific radionuclides found in each commodity.³⁰ This can help officials, unfamiliar with the radiative properties of NORM, in interpreting alarms from RIIDs during a secondary inspection, by facilitating manual spectral matching to commodity information on the shipment manifest. Similarly, the approach adopted in this paper does not require the installation of new detectors or associated hardware. Instead it explores a new method for analysing information already generated by detection systems.

A New Approach – Characterising Nuisance Alarms using spatial gamma profiles

The research presented in this paper investigates whether it may be possible to characterise nuisance alarms caused by NORM at the primary scanning stage, through the application of data science methods to existing information generated by RPMs. This could in theory eliminate or significantly reduce the number of time intensive secondary and tertiary inspections that are currently performed. Focusing on the spatial gamma profile generated by a container when passed through an RPM, it examines whether this could be used to characterise its contents, through a comparison with profiles of known NORM shipments. Currently, the use of RPM spatial gamma profiles in the assessment process is limited due in large part to variations in the speed of the container through the RPM. If successful, the approach proposed in this paper would have the benefit of freeing up on-site officials' time to focus on difficult to characterise alarms, including potentially those caused by threat materials. It could also enable the lowering of alarming thresholds, by serving to significantly increase the number of primary RPM alarms that a maritime facility is able to handle. This would in turn increase the likelihood of detection systems picking up key threat materials such as HEU, which may be shielded by adversaries and present a low radioactive signature.

There is currently no fixed or constant speed at which containers are driven through RPMs, resulting in spatial gamma profiles of varying lengths and shapes, which are challenging to interpret. Widely varying container speeds through RPMs are a common occurrence, as illustrated by the real-life dataset analyzed in this study, where occupancy periods ranged from 5.2 seconds to 33.8 seconds.³¹ The impact this can have on spatial profiles is illustrated in Figure 1, which shows the results of an experiment where the same container of NORM was passed through a RPM multiple times at different speeds. This results in significant distortion of the spatial gamma profiles generated. Consequently, RPM spatial gamma profile information is currently only useful for identifying clear anomalies such as a strong unshielded radioactive source.

Figure 1: Gamma Radiation Profiles for an alarming container passed through the same RPM at different speeds (Reproduced from IAEA Report).³²

This study utilises the data science technique of DTW to account for variations in container speed so that spatial profiles can be mathematically compared and a degree of dissimilarity between them calculated. It is hypothesised that this degree of dissimilarity will be small between shipments of similar NORM commodities relative to shipments of other NORM commodities. For example, different shipments of ceramics would have a similar warped spatial gamma profiles relative to say shipments of fertiliser. If true this approach could be used to differentiate between NORM shipments, grouping similar alarming occupancies and linking these to a specific commodity type. This is explored using hierarchal agglomerative clustering, a common technique for grouping objects based on their similarity. If valid and following the development of a reference database of warped spatial gamma profiles for

common NORM commodities, then this approach could be used to categorise nuisance alarms at the primary scanning stage.

Times Series and the Analysis of Real-World Data through Dynamic Time Warping

RPM spatial profiles can be considered as time series – a sequence of gamma counts indexed in time as a container is passed through a detector. Time series are most simply compared through calculating the Euclidean distance – the shortest path between points on both series that occur at the same time. This can be a useful metric for comparing the similarity between series if they are in phase i.e. with similar events occurring at the same exact moment. However, as previously discussed variations in container speed through an RPM mean that corresponding peaks and troughs will occur at different times, negating the use of this metric. For example, if the Euclidean distance were used to compare the RPM spatial gamma profiles in Figure 1 it would erroneously conclude that they were caused by different as opposed to the same shipment.

Thankfully, the comparison of time series that are out of phase is a commonly encountered problem in real-world events. For example, in automatic speech recognition where there can be considerable variation in different individuals' speaking speeds and pronunciation. Similar challenges can also be found in signature matching, music and signal processing and even in the rehabilitation of stroke victims.³³ A widely used technique, which can account for temporal variations in these and other types of time series, so that they can be compared, is Dynamic Time Warping (DTW). DTW calculates the best non-linear alignment between two series, matching similar features even if they are out phase.³⁴ The difference in approach between Euclidean matching and non-linear DTW matching is illustrated visually in Figure 2, for two example timeseries of differing lengths. Here the black lines show how corresponding points are matched and subsequently compared using each technique. For these two example series, DTW clearly provides a better matching of corresponding peaks and troughs.

Figure 2: Comparison of Euclidean matching versus non-linear Dynamic Time Warping Matching for two example time series.

DTW functions by effectively modifying or warping time series along an optimal path, which considers all local compressions, shifting and minimising the cumulative distance between aligned points. Consider two time series $T_A = (t_{A1} \dots t_{Ai} \dots t_{AN})$ and $T_B = (t_{B1} \dots t_{Bj} \dots t_{BM})$, of different lengths N and M , with points occurring at different times. These can be used to construct a matrix, $C \in \mathbb{R}^{N \times M}$, containing the distance between every point in series X with respect to every point in series Y .

$$C \in \mathbb{R}^{N \times M} : c_{i,j} = \|t_{Ai} - t_{Bj}\|, i \in [1 : N], j \in [1 : M]$$

There are several ways to calculate the distance between points across different series. This study used the Manhattan, or city-block metric, due to its ability to account for differences between series with high levels of similarity.³⁵ As small differences between RPM spatial gamma profiles could potentially be significant, for example, in the case where low activity shielded HEU is purposefully hidden within a shipment of NORM. Rather than taking the shortest Euclidean distance between two points, the Manhattan metric measures the distance along axes at right angles. For example, in a plane with point 1 at (x_1, y_1) and point 2 at (x_2, y_2) , the Manhattan distance is $|x_1 - x_2| + |y_1 - y_2|$.

The correspondence between the points in different series is then established through a warping path $\Phi = (\phi_t, \psi_t)$ where $t=1, \dots, T$, under the following constraints, namely:

- (1) *Start-point constraint.* The warping curve is anchored at the origin: $\phi_1 = \psi_1 = 1$;
- (2) *End-point constraint.* A global alignment is required, and the mapping covers both time series completely: $\phi_T = N, \psi_T = M$;

- (3) *Monotonicity restriction.* No ‘time loops’ are allowed in the mapping: $\phi_t \geq \phi_{t-1}$ and $\psi_t \geq \psi_{t-1}$;
- (4) *Step-size condition.* This limits the warping path from long jumps (shifts in time) while aligning sequences.³⁶

The start- and end-point constraints serve to guarantee that the alignment does not only partially consider one of the series. The monotonicity restriction and step-size condition ensure that the alignment path does not go backwards or jump in time, which could omit potentially important features.

The optimal warping path, which minimises the distance between points in the two series subject to the above constraints, is then calculated:

$$\Phi = (\phi_t, \psi_t) = \arg \min_{\phi_t, \psi_t} \sum_{t=1}^T \frac{d(x_{\phi_t}, y_{\psi_t}) m_{t,\Phi}}{M_\Phi}$$

Here x_{ϕ_t} and y_{ψ_t} are the elements of the warped input time series, d is the local distance function, $m_{t,\Phi}$ is a local weighting coefficient and $M_\Phi = \sum m_{t,\Phi}$.

A measure of dissimilarity between time series, can then be worked out by summing the Manhattan distance between the points, which have been matched up through DTW. Represented by the following cost-function:

$$c_\Phi(T_A, T_B) = \sum_{t=1}^T c(x_{Ai}, y_{Bi})$$

To avoid unfairly favouring short series owing to the cumulative sum element of this cost-function, this is normalised to give the average per-step dissimilarity, known as the pairwise distance.

RPM Alarming Dataset – Overview

This study’s dataset was provided to the research team by the IAEA under a Coordinated Research Project (CRP).³⁷ It included scanning records from multiple RPM lanes at maritime facilities in three countries, in the form of ‘daily files’.³⁸ These contain conveyance information on all alarming and non-alarming containers that are passed through a RPM over a twenty-four hour period. The officials at each site also provided additional information relating to the shipment manifest for alarming occupancies. Crucially for this study it included a description of the declared container contents and the corresponding 6-digit Harmonised

System (HS) code. HS codes are an international nomenclature used to classify traded goods for customs purposes.³⁹ At the international level these are six-digit product codes, where specific commodities are classified within a hierarchical structure composed of chapters, headings and sub-headings. For example, all ceramics are within chapter 69, within which bathroom ceramics come under heading 10, with all non-porcelain, non-china ceramics under sub-heading 90. Consequently, a shipment of non-porcelain, non-china bathroom ceramics will be given the HS code 691090.

A total of 720 usable alarming records triggered by NORM were identified in the dataset. These were then further separated into individual lanes, before comparative calculations were performed. This was done in order to minimise the influence of local factors, on the gamma radiation received. How best to account for variations in local factors is a key area of focus within the aforementioned IAEA CRP. However, given that these research efforts are still on-going a decision was taken to isolate these factors in order to concentrate on accounting for variation in speed in this initial study. Splitting the dataset into specific RPM lanes and analysing the alarming occupancies in each individually had the unavoidable negative effect of reducing the size of the dataset across which comparisons could be made. Nevertheless, in the most populous lane, the results from which are shown later in this paper, there were still over 150 records which could be compared. This was deemed sufficient to at least explore the potential utility of DTW and agglomerative hierarchical clustering in this proof of concept study.

Dynamic Time Warping of RPM Spatial Profiles – Preliminary Analysis

Initial efforts to explore the potentially utility of DTW in comparing and contrasting alarming RPM spatial profiles, involved the random selection of handfuls of alarming occupancies within specific lanes. The DTW pairwise distance for these profiles was then calculated and used as measure of their dissimilarity.⁴⁰ Results obtained from applying DTW to these very small trial datasets was promising, with the relative pairwise distance proving a useful metric for distinguishing between different types of commodities. An example from one of these initial tests, involving the comparative analysis of five RPM alarming profiles is shown in Figure 3 and Table 1. According to the supplied HS-codes three of these five alarms were triggered by shipments of fertiliser (HS-code 310490) – the red, green and gold profiles. The other two were triggered by shipments of ceramics (HS-code 691090) – the blue profile and clay (HS-code 240840) – the purple profile. Examining the RPM spatial gamma profiles visually, in Figure 3, the red and gold profiles are almost identical, while the green profile, despite having a similar shape has a shorter time series, as a result of being moved through the RPM at higher speed.

Figure 3: RPM spatial profiles for five alarming occupancies with corresponding HS codes.

Simple Euclidian matching would identify the green profile as considerably different from the red and gold profiles as their peaks and troughs occur at different point in time. DTW takes this variation into account, with calculations performed showing there is a comparable level of dissimilarity (a pairwise distance of 0.32, 0.53 and 0.55) between the three profiles. This is shown for all five profiles in the pairwise distance matrix in Table 1, with the level of dissimilarity between the shipments of fertiliser considerably less than their dissimilarity with respect to the shipments of ceramics and clay. It is also considerably less than the pairwise distance (0.93) between the shipments of ceramics and clay. Consequently, for these five records the pairwise distance can be used to identify that three of shipments are of the same commodity while the other two shipments contain different commodities.

	1 (Blue) (691090)	2 (Green) (310490)	3 (Red) (310490)	4 (Purple) (250840)	5 (Gold) (310490)
1 (Blue) (691090)	0	1.33	1.28	0.93	1.34
2 (Green) (310490)	1.33	0	0.53	1.50	0.55

3 (Red) (310490)	1.28	0.53	0	1.23	0.32
4 (Purple) (250840)	0.93	1.50	1.23	0	1.36
5 (Gold) (310490)	1.34	0.55	0.32	1.36	0

Table 1: Pairwise distance dissimilarity matrix for the five RPM profiles illustrated in Figure 3.

Clustering 'Warped' RPM Profiles

Following the completion of the aforementioned tests DTW was applied to larger datasets, for all the alarming records available from specific lanes. In assessing the ability of DTW to distinguish between similar and different commodities the widely used unsupervised data mining technique of clustering was employed. Clustering does not utilise any pre-existing knowledge or labelling of objects but instead relies on establishing an effective criterion for what is meant by 'similar' data. It attempts to 'identify structure in an unlabelled data set by objectively organizing data into homogeneous groups where the within-group-object similarity is minimized and the between-group-object dissimilarity is maximized'.⁴¹ As was the case for the preliminary tests the pairwise distance was used as the measure of dissimilarity between warped RPM spatial gamma profiles.

There are several different clustering methods that can be employed.⁴² Here agglomerative hierarchical clustering was selected, due to its ability to split a dataset into clusters naturally, without having to specify their number. This is important in the context of this study as the number of different commodities passing through an RPM is unknown in advance. Specifying this might have caused the datasets to split in an artificial manner. Agglomerative hierarchal clustering initially treats each record as a singleton (individual) cluster, before in a bottom-up step-by-step iterative process it pairs clusters that are the most similar, until they are all members of one complete cluster. This produces a tree-based representation of the records, known as a dendrogram.

The process of agglomerative hierarchal clustering is illustrated in Figure 4 for an example dataset of six records, simply labelled with numbers from "0" through "5". The order of the six records from left to right is not sequential according to their labels but arranged so that the incremental clustering approach can be clearly shown. Here each record starts as its own

singleton cluster before being paired and merged together into larger clusters as the measure of dissimilarity is increased – moving 'up' the vertical axis of the dendrogram. In the first step records 2 and 5 are paired, in step two records 3 and 4 are paired, in step three record 0 is merged with records 3 and 4, in step four record 1 is merged with records 3, 4 and 0 and finally in step five all records are merged into a single cluster. This demonstrates that records 2 and 5 are similar to one another but considerably different to any other record in the dataset only finally clustering with these at high levels of dissimilarity.

Figure 4: Dendrogram illustrating the process of agglomerative hierarchical clustering for a small dataset of six records, labelled 0 to 5, with the measure of dissimilarity on the vertical axis. The branch linking records 2 and 5 is colored green to illustrate that they are similar to one another but considerably different to any other record.

In determining how clusters are merged at each step there are several linkage methods that can be used to weigh their relative difference, based on their constituent records.⁴³ The utility of the following commonly used methods were explored in this study:

- Single link – Mergers are decided by the minimum pairwise distance value between any of the records within two clusters (i.e. the similarity of their most similar members);
- Average link – Mergers are decided by the average pairwise distance value between all the individual records within each of the two clusters;

- Complete link – Mergers are decided by the maximum pairwise distance value between any of the records within two clusters (i.e. the similarity of their most dissimilar members).

In this study warped RPM spatial gamma profiles were grouped, based on their pairwise distance, via agglomerative hierarchical clustering. The results from the most populous RPM lane from our dataset, containing 153 alarming occupancies, are illustrated as dendrograms in figures 5, 6 and 7 for single, average and complete link cluster merging. In each figure the y-axis provides a measure of the dissimilarity between commodities, with individual alarming occupancies represented under the x-axis. The three most common commodities, extracted from the HS codes on the shipment manifests, were glazed ceramics (HS-code 690890), ceramic bathroom fixtures (HS-code 691090) and fertiliser (HS-code 310490). The alarming occupancies for these are represented in figures 5, 6 and 7 as three vertical red dots (glazed ceramics), two vertical yellow dots (ceramic bathroom fixtures) and four vertical blue dots (fertiliser), with other commodities which were far less prevalent within the dataset represented as a single green dot.

Figure 5: Single link clustering for DTW RPM spatial profiles.

Figure 6: Average link clustering for DTW RPM spatial profiles.

Figure 7: Complete link clustering for DTW RPM spatial profiles.

It can be clearly seen that for each of the three linkage methods tested, that there is a preferential grouping of similar commodities. Demonstrated by the clusters of red, yellow and blue records underneath the x-axis. It should be noted that this grouping is not perfect, although this is to be expected with real world data.

Integrating DTW and Clustering into RPM Alarm Assessment

The practical application of this method would involve comparing the warped spatial gamma profile for a specific shipment against a database of warped spatial gamma profiles for common NORM commodities. Agglomerative hierarchical clustering would be used to associate the alarming shipment with a particular commodity type. The strength of this association would also be calculated, based on level of dissimilarity between the warped spatial gamma profile and other members of the commodity group i.e. where the alarming shipment fits within a particular cluster. This would then be checked against the shipment manifest for any inconsistencies.

Clearly, if this method grouped the cargo with a commodity that was different from what was listed on the shipment manifest then a secondary inspection would be triggered in order to investigate this discrepancy. However, if there was a match then a decision would have to be made by the on-site official, based on the strength of association, whether the cause of the alarm had been adequately resolved and the container could be returned to the supply chain or whether a secondary inspection should be launched. For example, utilising Figure 5, if the

warped spatial profile of a declared shipment of bathroom ceramics was to fall within the strong cluster of yellow records (that can be observed towards the left of centre) then it could be reasonably assumed that the information recorded on shipment manifest was accurate and complete. The container could then continue on its journey without the need for further investigation. However, if the warped spatial profile was to fall within the red or blue clusters towards the left or right of Figure 5, then it would be highly likely that a commodity other than bathroom ceramics was contained within the shipment and consequently a secondary inspection would have to be launched to investigate this further.

For this approach to be operationalised, a large and comprehensive database of warped RPM occupancies against which comparisons could be made would need to be constructed. Ideally containing hundreds if not thousands of occupancies for common commodity types. Databases could be constructed for individual lanes or at the facility, national or even international level if it proved possible to adequately account for the influence of local factors, discussed previously. Ideally databases would be populated with records from shipments that had their NORM cargo unambiguously confirmed through secondary or tertiary inspections. As highlighted previously there already exists hundreds of thousands of alarming records that could potentially be drawn upon for this purpose.⁴⁴ New confirmed alarming records would be added over time, increasing the size of the dataset against which comparisons could be made.

Conclusions and Future Work

Identifying key nuclear threat materials during border monitoring is a challenging task. This is accentuated in environments where there exists significant shipments of NORM and commercial radioactive sources, which trigger nuisance alarms. Currently, these are resolved through the use of time-intensive secondary and tertiary inspections. This paper has explored an alternative approach to assessment, involving the characterisation of nuisance alarms at the primary scanning stage. Rather than suggesting the development of a new type of detector, such as a SPM, it proposes the use of data science tools to extract new valuable insights from information already generated by currently deployed RPMs. Focusing on the RPM spatial gamma profile, DTW was used to account for differences in container speed so different alarming occupancies could be compared. The application of agglomerative hierarchical clustering to these warped profiles, showed a preferential grouping of similar NORM commodities. Following the development of a reference database, this approach could in theory be used to identify the likely commodity within a container and hence the cause of an alarm, without the need for additional inspections. Given the relatively small dataset it is difficult to precisely estimate the operational gains from the future adoption of this

technique. However, the strong groupings of similar commodities observed in Figures 5, 6 and 7 suggest that it could resolve a significant fraction of alarms caused by NORM.

Nevertheless, despite these promising findings, it should be emphasised that this study represents exploratory data analysis, an initial attempt to examine the utility of data science tools in support of radiation detection for border monitoring. This is due to the relatively small size of the dataset across which comparative analysis could be run. Its results should be confirmed through further work involving larger datasets with ideally thousands of alarming NORM occupancies. Datasets of this size would also enable a quantitative measure of the quality of clustering for a particular record to be determined. For example, if a particular record is a relative outlier within a particular cluster or if it has high levels of similarity to other records. This is an essential step in the development of a practical tool based on this approach, as the quality of clustering would likely determine whether or not on-site officials will allow a container back into the supply chain or launch a further investigation.

Future work could also look to explore whether the approach outlined in this paper could be used to classify commercial radioactive shipments and even possible threat materials. Given its comparative approach, in theory there is no reason it could not be extended to non-NORM alarming occupancies, as long as an appropriate dataset against which comparisons could be made could be constructed. However, this may pose a particularly difficult challenge for threat materials, given the almost unlimited number of potential smuggling scenarios. As these would involve unknown amounts of material and shielding and potentially the placement of smuggled materials in NORM shipments. Here a potentially fertile line of research would be instead to explore how, for example, the insertion of different quantities of threat materials into a container of NORM would affect the quality of clustering within specific commodity types. It would also be interesting to probe the limits of the approach advocated in this paper with regards to container speed i.e. explore whether there is a maximum speed at which comparisons between gamma spatial profiles utilising DTW become ineffective. This could be accomplished by passing the same container of NORM through an RPM multiple times, increasing the speed until it was no longer possible for it to be identified as the same shipment.

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Appendix: Alarming Dataset and Pre-Processing

The data for this research was provided to King's College London by the IAEA, it was collected from maritime facilities in three countries, all from road as opposed to rail-based RPMs. Information provided included RPM 'daily-files' containing 24-hours of data on the count rates observed by RPM gamma and neutron detectors. Also included was information on the key RPM settings such as alarm thresholds, detector type and fluctuating background radiation levels. 'Daily-files' are relatively large containing 10,000s of lines of data, these were cleaned and pre-processed to reveal a total of 720 alarming occupancies, where the gamma radiation received had crossed above the pre-set alarming threshold. For these alarming records spatial gamma profiles were created from the gamma readings captured every 0.2 seconds as the container passed through the RPM.

Information related to the commodity for alarming records was also made available, in the form of a Microsoft Access Database file. This had been originally created by the on-site official, drawing on information from the shipment manifest. This included the HS-code of the commodity contained within and its weight. Unfortunately, not all alarming occupancies could be associated with an HS-code as this had not been inputted correctly for every record. As this study relies on ultimately associating alarms with specific commodities, records that could not be assigned an HS-code had to be removed. This work also requires gamma readings to be normalised by weight so that shipments of different weights could be compared. This was done by subtracting the background radiation before dividing by weight. Accurate weight information is therefore essential, however, here it was clear that for certain cases this had been inaccurately recorded and so these records were also disregarded. Finally, records were also removed if the gamma count readings produced were obviously erroneous. For example, there was a series of records taken in succession which had profiles with an extended tail, far longer than for other records. This is likely to have occurred due to the container not being completely evacuated from the RPM after scanning, possibly due to the formation of a traffic jam, where for a period of time trucks were unable to drive away.

The result of this pre-processing stage reduced the total number of records from over 1,000 to 720. Although not the focus of this study clearly there is room to improve local processes for capturing RPM data so that it can be used in analysis of the type conducted here. In order to try and minimise the influence of other local factors that could affect the gamma radiation received a decision was also taken to separate our analysis into sub-groups of commodities passing through five specific RPM detectors. This further divided our data into sub-sets of 153, 45, 41, 40 and 37 records. As noted in the main body of this article, the small size of these

datasets means that the findings presented in this report, which are illustrated for the most populous lane, should be treated as preliminary.

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